Interaction Region at C0: Preliminary Lattice Studies

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Introduction

The purpose of this note is to document preliminary work performed to look into the possibility of adding a third interaction region to the Tevatron with the objective of accommodating a collider B-physics test experiment. The addition is to be performed at minimal cost, without disrupting the existing experimental program. In the context of this note, the general specifications for the insertion are assumed to be as follows:

- $\beta^* = 3.5$ m
- The insertion must be fully matched into the Tevatron i.e. $\beta_{x,y}$, $\alpha_{x,y}$, $\eta_{x,y}$ and $\eta'_{x,y}$ must match the existing lattice functions at the insertion boundaries.
- Space must be allocated for additional electrostatic separators to bring the beams into collision.
- Preliminary concept for the detector calls for a ± 6 to ± 8 T-m iron-dominated conventional analysis dipole magnet. Two compensating dipoles are used to correct the orbit distortion. Superconducting compensating dipoles are employed to save space.
- The spectrometer longitudinal extent is expected to be ± 9.8 m minimum. ± 7.8 m of free space between the IP and the first low beta quadrupole is required to accommodate the analysis magnet. The compensating dipoles, quadrupoles and end boxes can poke into the muon detector. This obviously affects the minimum angle muons that can be detected.

Background

The Tevatron lattice is a conventional FODO lattice. At six locations located symmetrically around the ring, the basic cell pattern is interrupted in favor of special insertions. At the A0, C0, E0 and F0 locations, these insertions provide long, dispersion free straight sections necessary for injection, extraction and RF acceleration. At B0 and D0, low-beta insertions focus the colliding beams.

The A0 region is reserved for TeV slow extraction and collider aborts. The F0 location is used for RF cavities and will also be used for injection beamlines from the Main Injector. The only locations available are are E0 and C0. While C0 is currently the site of the fixed target proton abort, E0 is free. C0 appears to be a better choice given the fact that some infrastructure is already in place, which is not the case at E0. It is conceivable that the fixed target abort could be dismantled and/or relocated.

Insertions are usually designed to be optically matched to the regular lattice. An insertion generally replaces an integer number of cells and is designed to satisfy periodic boundary conditions i.e. $\Psi(s_1) = \Psi(s_2)$ where Ψ represents the linear lattice functions $\beta_{x,y}, \alpha_{x,y}, \eta_{x,y}, \eta'_{x,y}$ at both extremities (s_1 and s_2). Periodic boundary conditions ensures that the lattice functions are not perturbed outside of the insertion itself; when they are not satisfied, the perturbations may or may not be consequential and must be accessed. For example, a dispersion perturbation in the injection region would cause a mismatch of the injected beam and result in emittance growth. In the Tevatron, dispersion is known not to be matched exactly at the extremities of the straight sections. As a consequence, a new insertion should be designed to match the lattice functions of the whole ring.

The matching problem can be summarized as follows: given a set of lattice functions Ψ_1 at one extremity of a beam line, the lattice functions at the opposite extremity are given by the relation:

$$\Psi_2 = R\Psi_1 \tag{1}$$

where R is the transfer matrix, uniquely defined by the geometry and strength of the optical elements. Note that due to the symplecticity of the dynamical equations, not all entries in the matrix R are independent.

To the extent that the phase advance $\mu_{x,y}$ is unconstrained, a completely matched insertion can be realized with a minimum of eight free parameters. In practice only six are needed because there is no vertical dispersion (i.e. $\eta_y(s) = \eta'_y(s) = 0$. In principle, one can use any combination of lens positions and strengths to obtain a match, but a fixed geometry solution with independent gradients is often the only practical way to match a range of optical conditions.

Note that when there are no dipoles in a beamline, the horizontal dispersion can be considered as a betatron oscillation (there is a dispersion invariant) and the total number of free parameters is reduced to five.

In a low beta insertion, there is usually no optical element between the beam waist and the nearest quadrupole. In that case, the betatron amplitude grows quadratically with the distance s from the point of minimum beam cross section. This can be easily derived by substituting the standard form for betatron motion

$$x(s) = A\beta^{1/2}(s)\cos\Psi(s) \tag{2}$$

into the horizontal equation of motion

$$x''(s) + K(s) = 0 \tag{3}$$

where $K(s)$ represents the focusing strength. This yields a differential equation for $\beta(s)$

$$\beta'''(s) + 4K(s)\beta'(s) + K'(s)\beta(s) = 0 \tag{4}$$

When $K(s) = K'(s) = 0$ this equation reduces trivially to

$$\beta''' = 0 \tag{5}$$

Choosing the origin at the waist where $\beta(0) = \beta^*$ and $\beta'(0) = 0$

$$\beta(s) = \beta^*[1 + s^2/\beta^{*2}] \tag{6}$$

The important result here is that the smaller β^*, the faster $\beta(s)$ grows. This fundamental dependence is a limiting factor on the space that can be made available for a physics detector since it determines the aperture of the low-beta quadrupoles.

Since the shape of the betatron function is known analytically in a drift space, it is a straightforward matter to calculate the phase advance between the innermost quadrupoles of a low beta section:

$$\Delta\mu = \frac{1}{\beta^*}\int_{-L}^{L} \frac{ds}{1 + s^2/\beta^{*2}} \tag{7}$$

$$= 2\tan^{-1}[L/\beta^*] \tag{8}$$

Usually $L >> \beta^*$ so the phase advance approaches π. This means that every interaction region will result in an increase of the horizontal and vertical tunes by approximately 0.5.

Luminosity

In the absence of a crossing angle, neglecting the details of the longitudinal distributions, and assuming identical Gaussian transverse distributions, the luminosity of a collider is given by

$$\mathcal{L} = \frac{I^2}{4\pi q^2 f B\sigma^2} \tag{9}$$

where the total current

$$I = N_b \cdot q \cdot f \cdot B \tag{10}$$

Here, N_b is the number of particles per bunch, q is the particle charge, f is the collision frequency, B is the number of bunches and σ is the transverse beam dimension.

Expressed in terms of the beam-beam strength parameter ξ, the luminosity becomes

$$\mathcal{L} = \frac{I\gamma\xi}{2qr_0\beta^*} \tag{11}$$

where

$$\xi = \frac{Ir_0\beta^*}{4\pi\gamma Bqf\sigma^2} \tag{12}$$

where $r_0 = q/m_0c$. ξ is a dimensionless parameter that characterizes the strength of the beam-beam interaction. To first order, the tune shift due to a beam-beam kick is simply

$$\xi \simeq \Delta\nu \tag{13}$$

Due to the nonlinearity of the the beam-beam kicks, the tune is amplitude dependent. The amplitude distribution in the beam results in a finite size footprint in the tune diagram. The maximum tune spread that can be accommodated avoiding resonances (typically resonances up to order 16 must be avoided) is roughly

$$\Delta\nu \simeq 0.02 \tag{14}$$

Assuming n crossing points, the maximum ξ per crossing point is

$$\Delta\nu/n \tag{15}$$

Assuming equal horizontal and vertical emittances $\epsilon_x = \epsilon_y = \epsilon$, we note that

$$\sigma = \sqrt{\beta^*}\epsilon \tag{16}$$

and

$$\xi = \frac{I r_0}{4\pi\gamma B q f \epsilon} \tag{17}$$

i.e. the beam-beam tune spread is *independent* of β^* and the transverse beam dimension.

In a collider such as the Tevatron the maximum current is usually limited by beam-beam effects. Under this condition, the introduction of a third interaction region would reduce the theoretical luminosity available to `B0` and `D0` by 33%.

In the Main Injector era, it is expected that particle loss due to collisions will be non-negligible. This effect depends on the beam transverse dimensions and may therefore have some influence on the optimal choice of β^* in a new interaction region. It is likely that the final choice will be driven by other considerations such as size of the detector, magnet apertures, costs and availability.

Low Beta Insertion Design

The existing low-beta insertions at B0 and D0 provide a good starting point. Both insertions are essentially identical. The insertion lattice at D0 and the corresponding lattice functions calculated for a full ring are shown in figure 2. The lattice functions (calculated) at locations C43 ad D14 (considered as the insertion boundaries) are presented in table . The magnet layout is shown schematically in figure 1. The main triplet is constituted of the quadrupoles labeled `Q2`, `Q3` and `Q4`. These are strong quadrupoles whose function is to squeeze the beam to its final size. The size of the beta function as it enters the triplet is controlled with the quadrupoles labeled `Q1`. The other quadrupoles provide enough degrees of freedom to match all the lattice functions to the rest of the ring. Note that there are more free parameters than is absolutely necessary to simply provide a match: one must also keep the the beta function amplitude and the gradients within reasonable limits. Furthermore, the dispersion must remain small and vanish at the beam waist. The magnet labeling scheme is purely historical and is, unfortunately, inconsistent in many of documents published internally.

location	β_x	α_x	D_x	D'_x	β_y	α_y
	m		m		m	1
C43	30.729	0.567	3.769	-0.064	97.359	-1.866
D14	32.125	0.619	3.357	-0.099	97.854	-1.885
B43	28.535	0.550	3.784	-0.066	93.298	-1.763
C18	31.783	0.662	3.370	-0.096	97.562	-1.846

Table 1: Lattice functions at locations C43,D14 and B43,C48 (calculated).

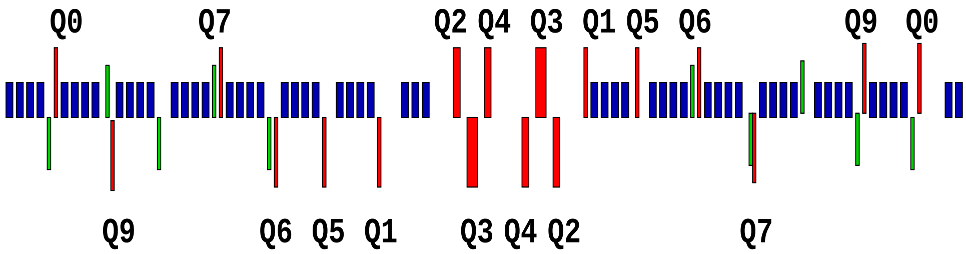

Figure 1: Present Low Beta Insertion Lattice at D0.

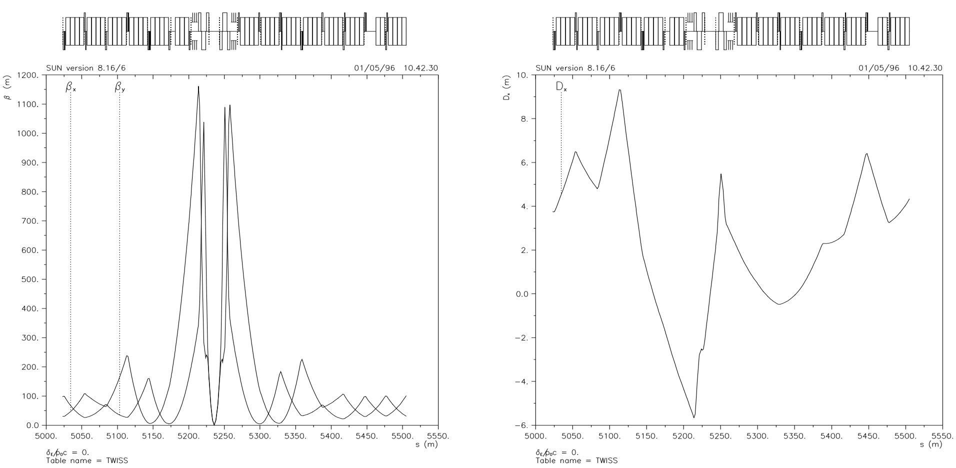

Figure 2: Left:Horizontal and vertical beta functions across the insertion. Right:Horizontal dispersion across the insertion. Calculation based on a full ring.

A preliminary solution based on a final doublet

The existing low beta insertions at B0 and D0 use a quadrupole triplet to squeeze the beam down to 0.35 m. A triplet is required to control the maximum amplitude of the beta function in the quadrupoles to get reasonable apertures. In the scenario considered here, the fact that we only need to focus the beam down to 3.5 m makes it possible to consider a final doublet configuration in order to save space and to reduce cost. A

Quad	Gradient[T/m]	Length [m]
Q0	-9.873413952034	0.635
Q9	-9.322136085317	0.635
Q7	27.002844016035	0.635
Q6	23.611156707191	0.606425
Q5	72.012326827177	1.401826
Q1	-1.173972904129E2	1.401826
Q3	86.180331331218	5.8928
Q4	-1.523301390552E2	3.3528
Q2	0.0	0.0
Q2	0.0	0.0
Q4	-1.523301390552E2	3.3528
Q3	86.180331331218	5.8928
Q1	-86.225501626326	1.401826
Q5	-47.399034105089	1.401826
Q6	5.877532277144	0.606425
Q7	12.533298001923	0.635
Q9	-14.038460846525	0.635
Q0	-8.550064455209	0.635

Table 2: Gradients and lengths corresponding to the doublet solution.

preliminary solution, (Peter Garbincius) based on a doublet configuration is shown in figure 3. While this solution is not optimal in any way, it constitutes a proof of technical feasibility. The corresponding gradients and magnet lengths are presented in table 2. The quadrupoles labeled `Q2` in figure 1 have been turned off. `Q3` and `Q4` have been moved away from the center. The distance between the low beta point and `Q4` has been increased from 7.6229 m to 11.435 m.

Future Work

The material presented in this note is very preliminary. Many issues need to be addressed including:

1. Interaction trade-offs between experiment requirements and low-beta design in terms of accelerator components vs free space.

2. A workable electrostatic separator configuration, including possibility of a 100 μrad crossing angle.

3. Implications of a third interaction region on beam stability, lifetime etc ... (Beam-beam effects, chromaticity etc ...)

4. Optimization of the number of magnets, lengths and gradients in view of items (1) (2) and (3) .

   (a) Consider availability, cost of magnets etc ...

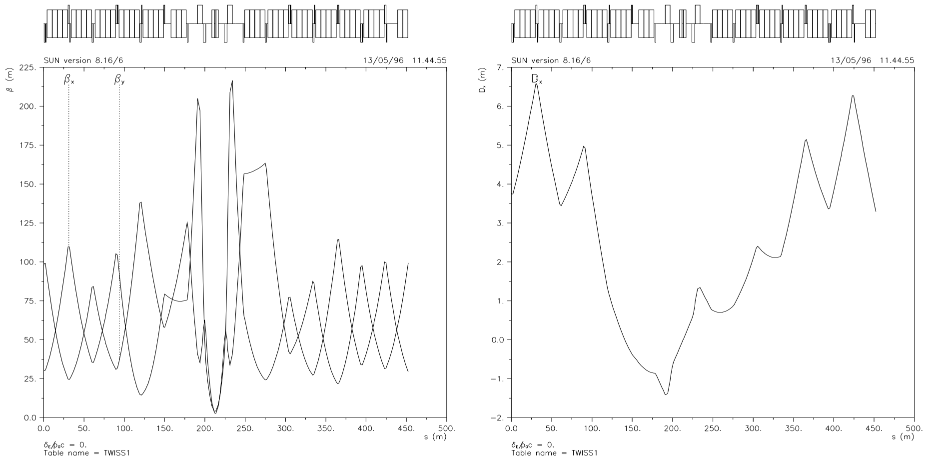

Figure 3: A doublet solution. Left: Horizontal and vertical beta functions across the insertion. Right:Horizontal dispersion across the insertion.

(b) Investigate higher performance quadrupoles and dipoles to increase free space for separators and experiments.

(c) Are the original low-beta components from `B0` available and useful ?

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